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New Constraints on Spatial Variations of the Fine Structure Constant from Clusters of Galaxies

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Abstract: We have constrained the spatial variation of the fine structure constant using multi-frequency measurements of the thermal Sunyaev-Zeldovich effect of 618 X-ray selected clusters. Although our results are not competitive with the ones from quasar absorption lines, we improved by a factor 10 and ~ 2.5 previous results from Cosmic Microwave Background power spectrum and from galaxy clusters, respectively.

Keywords: cluster of galaxies; Cosmic Microwave Background; varying fine structure constant; Sunyaev-Zeldovich effect

1. Introduction

Recently, large observational studies of Quasar (QSO) absorption lines claimed that the fine structure constant could vary over the sky with a dipolar modulation [1–5]. The direction of such a dipole is

comparable to the direction of other so-called anomalies and/or dipoles [6,7]. However, complementary analyses carried out on the Cosmic Microwave Background (CMB) power spectrum [8,9], and studying the effect of such modulation on the orbital motion of the major bodies of the solar system [10], do not report any detection. Since their sensitivity is, however, one thousand times worse than the one achieved with QSO data, there is a need to carry out tests with other observational datasets such as multi-frequency measurements of the thermal Sunyaev Zeldovich effect (TSZ, [11]) in cluster of galaxies.

The TSZ effect induces secondary anisotropies on the CMB power spectrum. Such anisotropies are usually expressed in terms of the Comptonization parameter (Y_c) as $\Delta T_{TSZ} = T_0 G(\tilde{\nu}) Y_c$, where $G(\tilde{\nu})$ is the TSZ spectral dependence, Y_c is proportional to the integral along the line of sight of the pressure profile of the intra-cluster medium, and T_0 is the current value of the CMB black-body temperature. Moreover, $\tilde{\nu} = h\nu(z)/k_B T_{CMB}(z)$ is the reduced frequency, k_B is the Boltzmann constant, h is the Planck constant and $T_{CMB}(z)$ is the CMB black-body temperature at the cluster location.

In the concordance Λ CDM model, the CMB black-body temperature is $T_{CMB,std}(z) = T_0(1+z)$. Any departure from such behavior should imply an extension of the concordance model. In particular classes of models, where a scalar field is coupled to the Maxwell F^2 term in the matter Lagrangian, the photon number conservation is violated. Thus, the violation of the standard $T_{CMB}(z)$ law is coupled to the variation of the fine-structure as

$$\frac{T_{CMB}(z)}{T_0} \sim (1+z) \left(1 + \epsilon \frac{\Delta\alpha}{\alpha} \right) \quad (1)$$

and their common origin implies that the coefficient ϵ is expected to be of order unity [12]; for example, in a somewhat simplistic adiabatic limit $\epsilon = 1/4$. Thus, if one is able to determine $T_{CMB}(z)$ at the cluster location using multi-frequency measurements of the TSZ effect, then Equation (1) can be used as a phenomenological relation to observationally test the spatial variation of α .

We apply the techniques developed in [13] to measure the TSZ emission at the location of 618 X-ray selected clusters. Then, we use such measurements to test the spatial variation of the fine structure constant. The article is organized as follows: in Section 2 we will describe the data; in Section 3 we will explain the methodology; in Section 4 we will illustrate and discuss our results; and finally, in Section 5, we will give our main conclusions.

2. Data

Galaxy clusters were selected from the ROSAT-ESO Flux Limited X-ray catalog (REFLEX, [14]), the extended Brightest Cluster Sample (eBCS, [15,16]) and the Clusters in the Zone of Avoidance (CIZA, [17]). The catalog lists 618 galaxy clusters for which all quantities of interest for our analysis are directly measured or derived: positions, spectroscopic redshifts, the central Comptonization parameter ($y_{c,0}$), the scale radius at which the mean overdensity of the cluster is 500 times the critical density (r_{500}), and the corresponding angular size $\theta_{500} = r_{500}/d_A(z)$. Here, $d_A(z)$ is the angular diameter distance of each cluster. At the location of each cluster we measure the TSZ anisotropies using the *Planck* 2013 maps (Maps were originally released in a Healpix format with resolution $N_{side} = 2048$ [18]). Data are available at <http://www.cosmos.esa.int/web/planck>.

In March 2013, the Planck Collaboration made publicly available its nine Nominal maps covering the frequency channels from 30 to 857 GHz. Since the TSZ effect has a peculiar spectral dependence

it can be distinguished from other components and reliably detected once the foreground emissions and the cosmological CMB signal are reduced. For that purpose, we apply a cleaning procedure, fully described in [13,19,20], to the High Frequency Instrument data (100–857 GHz), since they have better resolution and lower instrumental noise than the Low Frequency Instrument data (30–70 GHz). *Before applying the cleaning procedure, we remove the intrinsic CMB monopole and dipole from the Nominal maps* (We use the `remove_dipole.pro` facility of Healpix. It simultaneously performs a least square fit of the monopole and dipole on all the valid pixels and removes them from the map. More details can be found at <http://healpix.jpl.nasa.gov/html/subroutinesnode86.htm>). The cleaning procedure returns, for each Planck frequency channel, a foreground cleaned patch centered at the position of each cluster in our catalog. Then, in each patch and for each frequency, we measure the average TSZ temperature ($\delta\bar{T}/T_0(\nu)$) over discs with angular extent equal to θ_{500} . Hereafter, the averaged quantities are always evaluated on discs of radius θ_{500} and indicated with a bar. To assign an error bar to each of the measurements, we carry out 1000 random simulations. In each one, we evaluate the mean temperature fluctuations in patches randomly placed out of the cluster positions and clean using the same procedure adopted for the real cluster population. Finally, we compute the correlation matrix between different frequencies (C_{ij})

$$C_{ij} \equiv C(\nu_i, \nu_j) = \frac{\langle [\delta\bar{T}(\nu_i) - \mu(\nu_i)][\delta\bar{T}(\nu_j) - \mu(\nu_j)] \rangle}{\sigma(\nu_i)\sigma(\nu_j)}, \quad (2)$$

where the average was computed over all simulations, $\mu(\nu_i) = \langle \delta\bar{T}(\nu_i) \rangle$, and $\sigma(\nu_i) = \langle [\delta\bar{T}(\nu_i) - \mu(\nu_i)]^2 \rangle^{1/2}$. The square roots of the diagonal elements of the correlation matrix are the error bars associated to the TSZ temperature anisotropies of each cluster.

3. Methodology

To estimate the CMB temperature at the cluster location, as well as to constrain the spatial variations of the fine structure constant, we use a Monte Carlo Markov Chain (MCMC) technique to explore the corresponding relevant parameter space. Our pipelines employ the Metropolis-Hastings sampling algorithm [21,22] with different (randomly set) starting points, and the Gelman-Rubin criteria [23] to test the convergence and the mixing of each chain. Specifically, we compute the ratio of the variances in the target distribution, and require it to be $\mathcal{R} < 1.03$ (mathematical definitions are given in Section 3.2 of [24]). We run four chains that stop when they satisfy the criteria and contain at least 30,000 steps. Finally the chains are merged, and the expectation value of the 1D marginalized likelihood distribution is computed using all the steps.

First we need to estimate the CMB temperature at the cluster location. Having measured for each galaxy cluster the averaged TSZ emission as a function of frequency, we predict the theoretical counterpart at the same aperture $\Delta\bar{T}(\mathbf{p}, \nu_i)/T_0 = G(\nu_i, T_{CMB}(z))\bar{Y}_c$, where $\mathbf{p} = [T_{CMB}(z), \bar{Y}_c]$ are the free parameters of the model, and \bar{Y}_c is the averaged Comptonization parameter. Finally, we compute the likelihood $-2 \log \mathcal{L} = \chi^2(\mathbf{p})$ as

$$-2 \log \mathcal{L} = \chi^2(\mathbf{p}) = \sum_{i=0}^N \sum_{j=0}^N \Delta\bar{T}_i(\mathbf{p}) C_{ij}^{-1} \Delta\bar{T}_j(\mathbf{p}), \quad (3)$$

where $\Delta\bar{T}_i(\mathbf{p}) \equiv \frac{\Delta\bar{T}(\mathbf{p}, \nu_i)}{T_0} - \frac{\delta\bar{T}(\nu_i)}{T_0}$, and $N = 4$ is the number of data points (the four frequencies). Once our simulations reached the convergence criteria, we estimated the CMB temperature for each

individual cluster, and its 68% of confidence level error bar, from the 1D marginalized likelihood distribution. See [25] for a full description of the methodology. These measurements are used to estimate the α -anisotropies as

$$\frac{\Delta\alpha}{\alpha} = \epsilon^{-1} \left(1 - \frac{T_{CMB}(z)}{T_0(1+z)} \right). \quad (4)$$

Finally, we probe 3 different models allowing for a monopole (m) amplitude plus dipole (d) variation. Specifically, the first model assumes the functional form defined in [1] to fit quasar data (**Model 1**)

$$\frac{\Delta\alpha}{\alpha} = m + d \cos(\Theta), \quad (5)$$

where Θ is the angle on the sky between the line of sight of each cluster and the best fit dipole direction. Then, we fit the model used in [26] to the cluster data. Such a model (**Model 2**) allows a variation with the Λ CDM look-back time, $r(z) = \int \frac{dz'}{H(z')}$:

$$\frac{\Delta\alpha}{\alpha} = m + dr(z) \cos(\Theta). \quad (6)$$

Finally, to explore the possibility of an intrinsic dipole, we also try to fit the following relation to the CMB temperature measurements (**Model 3**)

$$\frac{\Delta T}{T_0(1+z)} = m + d \cos(\Theta). \quad (7)$$

For each model we analyze four different configurations of the parameter space: (A) $m = 0$ for the Model 1 and 2, and unity for Model 3, the direction of dipole is fixed to the one from QSO [1], while the amplitude vary in the interval $[-1, 1]$; (B) the direction is still fixed, but we also vary the monopole in the intervals $[-1, 1]$ for Model 1 and 2, and $[0, 2]$ for Model 3; (C) and (D) we repeat the configurations of (A) and (B) but we also vary the dipole direction over the whole sky.

4. Results and Discussion

Our results show that the monopole and dipole amplitudes are always compatible with their expected valued in standard cosmology within 1.5σ . The best constraints are: $m = 0.006 \pm 0.004$ and $d = -0.008 \pm 0.009$ for Model 1 (B), and $d = -0.003 \pm 0.003 \text{ GLyr}^{-1}$ and $m = 0.006 \pm 0.005$ for Model 2 (A) and (B), respectively. The direction of the “possible” dipole is always compatible with the one predicted from QSO in [1], but when they are varied the constraints on the monopole and dipole amplitudes are degraded since the number of free parameters is increased. Nevertheless, our best fit directions are always compatible with the one from QSO data [1,2] and other CMB anomalies [6,7], while they are several degrees away from the directions of the intrinsic CMB and the Dark Flow dipoles, from the kinetic CMB asymmetry, and from the CMB cold spot location [27–39]. All results are summarized in the Table 1 and, for easier comparison, the anomalies directions are plotted in Figure 1.

Since our analysis shows that the possible dipole direction coincides with the one obtained from QSO [1] and dark energy models [6,7], it could be interpreted as the fact that such dipoles, if confirmed with more extended and independent analysis, could represent signature of the failure of the Λ CDM model in favor of varying constant models or extended theories of gravity. Finally let us remark that, although

we are not competitive with the QSO constraint from [1], our best fits for Model 2 provide a precision improvement of a factor ~ 2.5 , while being compatible with the results in [26]. For Model 1, we improve on the previous constraints in [8,9] by a factor ~ 10 . The improvement is mainly due to the fact that previous analyses, based on the CMB power spectrum, need to fit not only all "standard" parameters of the cosmological model, but also the additional ones related to the variation of fundamental constants; as a consequence, the resulting constraints were less tight.

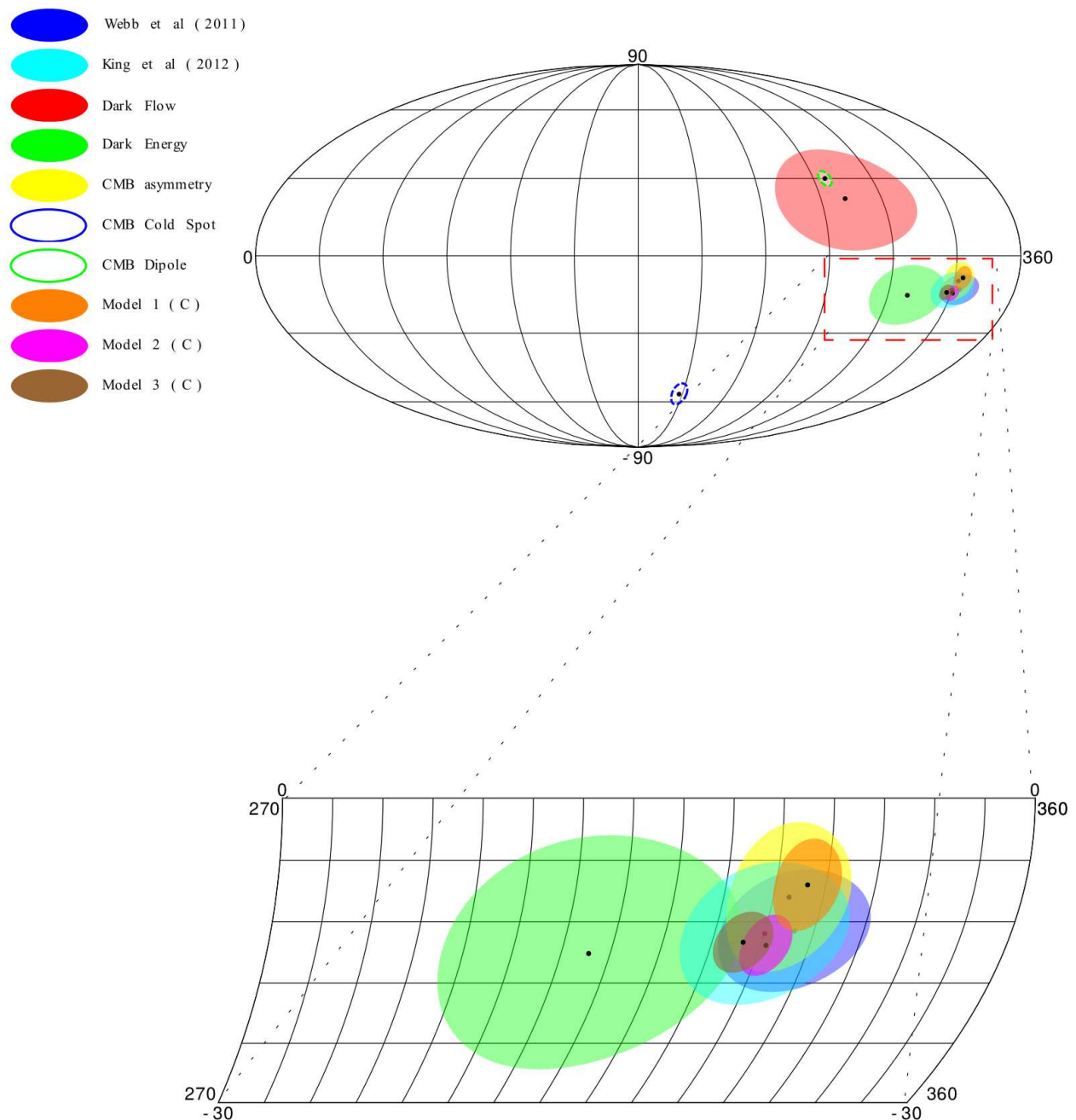


Figure 1. Directions in galactic coordinates for the spatial variation of the fine structure constant from [1,2] in blue and cyan, respectively, for the Dark Energy dipoles from [6] in green, Dark Flow direction from [27,30–33] in red, for the Cosmic Microwave Background (CMB) asymmetry from [7] in yellow, and for our results from the analysis (C) of models 1,2 and 3 in orange, magenta and brown, respectively. Finally, we also indicate in blue and green dashed circles the direction of the Cold Spot anomaly and the intrinsic CMB dipole, respectively [28,29,34].

5. Conclusions

We have considered a model in which the variation of the fine structure constant is coupled to the variation of the CMB temperature. Using Equation (1), we have constrained the spatial variation of

the fine structure constant using the Planck 2013 Nominal maps and a X-ray selected cluster catalog. First, we have cleaned the Planck maps and extracted the CMB temperature at the location of 618 X-ray selected clusters using the TSZ multi-frequency measurements. Then, we have carried out a statistical analysis to test three models allowing for monopole and dipole amplitudes, and describing both spatial variations of $\Delta\alpha/\alpha$ and of T_{CMB} itself. All results of our analysis are summarized in Table 1.

Table 1. Results of the analysis for Models 1, 2 and 3 from [25].

		m	d	RA (°)	DEC (°)
Model 1	(A)	0.0	-0.002 ± 0.008	261.0	−58.0
	(B)	0.006 ± 0.004	-0.008 ± 0.009	261.0	−58.0
	(C)	0.0	-0.030 ± 0.020	255.1 ± 3.8	-63.2 ± 2.6
	(D)	0.021 ± 0.029	-0.030 ± 0.014	255.9 ± 4.2	-55.3 ± 5.8
Model 2	(A)	0.0	$-0.003 \pm 0.003 \text{ GLyr}^{-1}$	261.0	−58.0
	(B)	0.006 ± 0.005	$-0.003 \pm 0.005 \text{ GLyr}^{-1}$	261.0	−58.0
	(C)	0.0	$-0.042 \pm 0.049 \text{ GLyr}^{-1}$	261.6 ± 16.1	-61.3 ± 2.7
	(D)	0.019 ± 0.011	$-0.027 \pm 0.051 \text{ GLyr}^{-1}$	245.0 ± 12.9	-56.0 ± 3.8
Model 3	(A)	1.0	-0.010 ± 0.008	261.0	−58.0
	(B)	1.001 ± 0.002	-0.003 ± 0.002	261.0	−58.0
	(C)	1.0	-0.020 ± 0.015	258.0 ± 1.2	-64.0 ± 1.1
	(D)	1.000 ± 0.0001	-0.018 ± 0.015	258.4 ± 1.9	-64.3 ± 2.6

Although at the present time galaxy clusters are not competitive with high-resolution spectroscopic measurements in absorption systems along the line-of-sight of bright quasars, our analysis was improved by an order of magnitude previous constraints by the Planck Collaboration [8] and by a factor ~ 2.5 the results from Galli (2013) [26].

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Author contributions IDM and CJM conceived the project and wrote the paper; IDM performed the data analysis; HE and DK provided the X-ray cluster catalog.

The authors declare no conflict of interest.

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